Extraction of Mobility Degradation and Source-and-Drain Resistance in MOSFETs

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ABSTRACT

A MOSFET model parameters extraction procedure that overcomes the difficulties of separating the effects of source-and-drain series resistance and mobility degradation factor is presented. Instead of the conventional direct fitting, the present procedure involves the use of indirect bidimensional fitting of the source-to-drain resistance of a single device, as obtained from the below-saturation output characteristics measured at several above-threshold gate voltages. The procedure is verified with a simulated long channel FinFET device with externally added resistances and is later applied to experimental planar bulk DRAM MOSFET devices with channel lengths ranging from 0.23µm to 2.0µm. The procedure is shown to be advantageous in terms of computational efficiency and it is appropriate even with high values of externally added series resistances. For the case of devices with various channel lengths, the accuracy of the procedure is improved if the value of R_{SD} is extracted from the shortest channel length. This value of R_{SD} could be used for extracting the other parameters for devices with longer channel.

Index Terms: MOSFET, mobility degradation, source-and-drain resistance, parameter extraction, indirect bidimensional fitting.

1. INTRODUCTION

Mobility degradation and source-and-drain series resistance are two model parameters of particular significance for MOSFET characterization. Unfortunately, they manifest themselves in a similar manner on the device's transfer characteristics. This fact complicates their extraction independently from one another. Some extraction methods have been proposed in the past to get around this stumbling block [1-7].

We present here a way to separate the effects of mobility degradation and source-and-drain series resistance. It is based on the bidimensional (V_{GS},V_{DS}) fitting of the source-to-drain resistance measured in above-threshold and below-saturation conditions. The procedure is first verified with simulated data from a long channel FinFET device with the presence of externally added resistances. It is then applied to experimental data from test DRAM MOSFETs of various channel lengths. The procedure's computational efficiency is satisfactory in terms of initial values range tolerance and number of iterations needed.

The extraction of the MOSFET model's parameters is commonly performed using direct optimization [1-2], by fitting the measured current-voltage characteristics to the above-threshold implicit drain current (I_D) equation in the triode region, using a simple universal mobility model [8]:

$$I_D = \frac{K}{1+\theta\left(V_{gs}-V_T\right)}\left(V_{gs}-V_T-\alpha\frac{V_{ds}}{2}\right)V_{ds} \quad , \quad (1)$$

where

$$V_{gs} = V_{GS} - I_D\frac{R_T}{2} \quad , \quad (2)$$

$$V_{ds} = V_{DS} - I_D R_T \quad , \quad (3)$$

$$K = \frac{W}{L_{eff}} C_{ox}\, \mu_o \quad , \tag{4}$$

$$R_T = R_{SD} + 2R_{ext} \quad , \tag{5}$$

V_{GS} and V_{DS} represent the externally applied gate and drain voltages, respectively, R_T is the total series resistance, R_{SD} is the parasitic source-and-drain series resistance and R_{ext} is an externally added resistance to both the source and drain terminals, μ_o is the low-field mobility,θ is the mobility degradation factor due to the gate field [8], α is a bulk-charge factor to globally account for threshold voltage dependence on channel potential due to depletion thickness nonuniformity along the channel [9], $L_{eff} = L_m - \Delta_L$ is the effective channel length, L_m is the mask channel length, and the rest of the parameters have their usual meaning. Although this model does not include carrier velocity saturation or other short channel effects, these effects may be included in the model without any loss of generality.

Using direct optimization on the implicit current equation 1 usually makes the extraction of R_{SD} and θ a difficult task, considering the already mentioned equivalent effect that the total source-and-drain series resistance and the mobility degradation have on the shape of the $I_D(V_{GS})$ characteristics. Instead, here we broaden our recently proposed procedure, based on performing bidimensional fitting to the measured source-to-drain resistance [7,10], and extract the parameters as functions of channel length for the experimental devices. The use of the indirect fitting procedure provides a clear advantage in computational efficiency, since it reduces by a factor of about 3 the number of iterations needed to converge to the correct values.

2. EXTRACTION PROCEDURE

The measured source-to-drain resistance defined by:

$$R_m \equiv \frac{V_{DS}}{I_D} \quad , \tag{6}$$

may be obtained from equation 1. After some algebra the following equation results:

$$a_{VD} V_{DS} + a_{VG}\left(V_{GS} - V_T\right) - 2R_m = 0 \quad , \tag{7}$$

where the two coefficients are given by:

$$a_{VD} = R_m R_T K(2\alpha - 1) - R_m{}^2 K\alpha + R_T{}^2 K(1-\alpha) + R_T\theta \tag{8}$$

and

$$a_{VG} = 2R_m{}^2 K - 2R_m\theta - 2R_m R_T K \quad . \tag{9}$$

The first step in the procedure is to extract the threshold voltage, V_T, value from the $I_D(V_{GS})$ characteristics at low V_{DS}, through any of the available V_T extraction methods [11]. We use here the transition method developed a few years ago [12]. Next, the parameters R_T, θ, α, and K, are extracted by bidimensional (V_{GS},V_{DS}) fitting of equation 7 to the source-to-drain resistance, R_m, obtained from the measured $I_D(V_{GS},V_{DS})$ data. A Levenberg–Marquardt type algorithm [13] with a step size of 10^{-3} and a tolerance of 10^{-10} is used for fitting equation 7 to the measured source-to-drain resistance.

Because the relative weight of R_{SD} within the measured R_m increases as channel length decreases, the value of R_{SD} is extracted from the shortest channel length device, when available, to get the best possible accuracy. Thereafter R_{SD} is assumed to be the same for the rest of the devices with longer channel lengths from the same batch. The remaining parameters θ, α, and K are then extracted for each channel length using this value. In order to corroborate the validity of the proposed method, we will study in section 4 the evolution of the extracted parameters as a function of the mask channel length.

3. VERIFICATION WITH SIMULATED DATA

We applied the procedure to an n-channel silicon triple-gate FinFET, with a channel doping of N_a=10^{15}cm^{-3}, gate work function Φ=4.7eV, L_m=10μm, fin width W_{Fin}=20nm, fin height H_{Fin}=60 nm and t_{ox}=2nm. The mobility models used in the simulations [14] were Klaassen's (Phillips) for low electric field, Lombardi's for surface roughness and Canali's for velocity saturation effects. There are 8 tridimensional simulations with the Sentaurus Device Simulator from Synopsys corresponding to the same device with 8 different values of externally added resistances, R_{ext}= 100Ω, 200Ω, 500Ω, 1KΩ, 2KΩ, 5KΩ, 10KΩ and 20KΩ. The externally added resistances are connected in series at both the source and drain terminals of the device. A threshold voltage of V_T= 0.49V was extracted from the transfer characteristics of the device with R_{ext}= 100Ω, at a low drain voltage of 10 mV, using the transition method [12].

Figure 1 presents the simulated output and transfer characteristics of the FinFET used in this study. We see in this figure that the plots seem to be merging together for a decreasing R_{ext} because R_{ext} is starting to be negligible with respect to R_{SD}.

For the case of this long channel FinFET device, we first extracted the value of the bulk-charge effect parameter α = 1.02 using the method presented in [9], which is very close to the approximation of α = 1 commonly used for long channel double gate devices. This approximation of α = 1 corresponds to a

first level of MOSFET modeling and leads to slightly larger relative errors than those obtained using the extracted value of 1.02, as will be shown later.

Once the value of V_T=0.49V is obtained, we proceed to extract the parameters R_T, θ and K, by indirect fitting of equation 7 to the simulated data using α =1.

Figure 2 presents the output characteristics and its corresponding source-to-drain resistance, R_m, for the case of an externally added resistance of R_{ext} = 100 Ω. The resulting model playbacks calculated by using the extracted parameters are also shown.

Figure 3 shows the extracted parameters vs the externally added resistance, using the classic value of the bulk-charge effect parameter, α =1. Parameters θ and K^{-1} exhibit fairly constant behavior as expected for a long channel device. On the other hand, the extracted R_T shows a linear dependence on R_{ext} with a slope of 1.99 which is close to the expected value of 2 according to equation 5. The value of the intrinsic R_{SD} corresponds to the R_T axis intercept (R_{ext}=0), as equation 5 indicates. In the present case, a value of R_{SD} = 8.35 KΩ is obtained, as shown in Fig. 3(a).

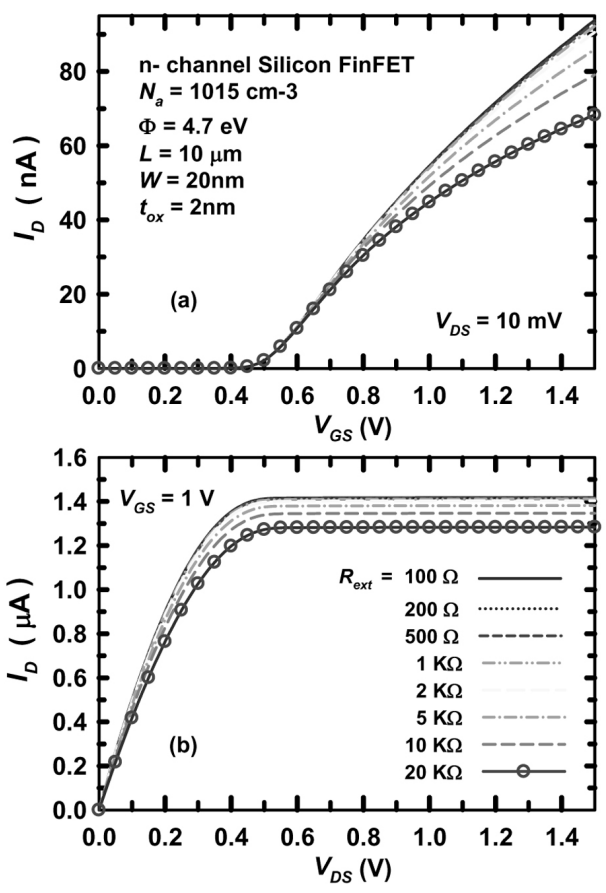

Figure 1. Transfer (a) and output (b) characteristics of the simulated FinFET for 8 values of external resistance. Plots seem to be merging together for a decreasing R_{ext} because R_{ext} is starting to be negligible with respect to R_{SD}.

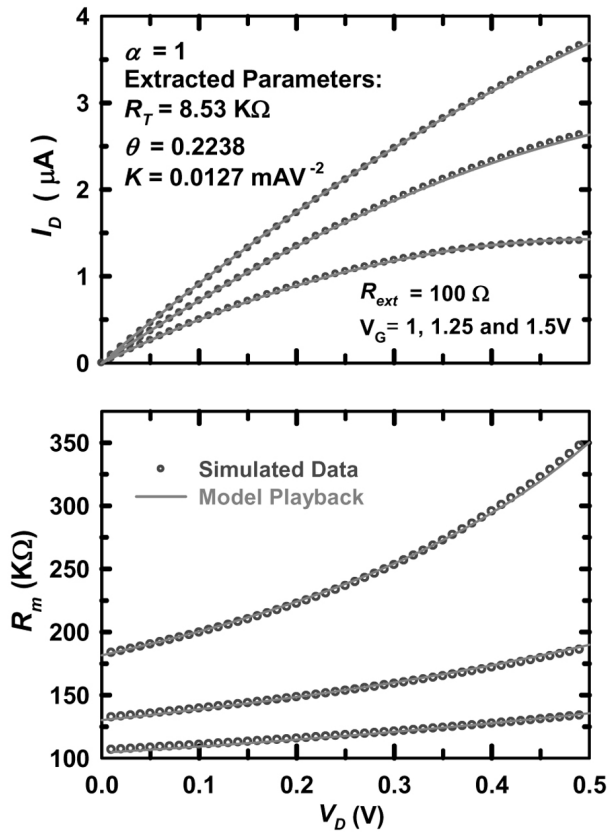

Figure 2. Output characteristics (a), and corresponding source-to-drain resistance (b), of the FinFET with R_{ext} = 100Ω. Also shown are the model playbacks (red solid lines) obtained by using the extracted parameters indicated in the inset.

It should be pointed out that if no externally added resistances are present, this last step would be unnecessary since R_T=R_{SD} and R_{SD} would be directly extracted.

In order to consider the effect of using either the classic approximation of α =1, or the extracted value of α=1.02, we calculated the relative errors for both cases. The comparison is done using V_{GS}=1V and an external resistance R_{ext}=20KΩ.

Figure 4 shows that the relative errors are only lightly higher when using α=1, hence this value is a good approximation for this long channel double gate device.

4. APPLICATION TO EXPERIMENTAL DEVICES

The extraction procedure was applied to experimental test planar bulk DRAM MOSFETs with a SiO_2 gate oxide of 4nm, a width of 10μm and mask channel lengths of L_m=0.23μm, 0.60μm, 1.00μm and 2.00μm. The drain currents for the devices were measured below-saturation as a function of drain voltage at three above-threshold values of gate voltage.

Figure 5 presents the output characteristics of the shortest channel device (0.23μm), together with

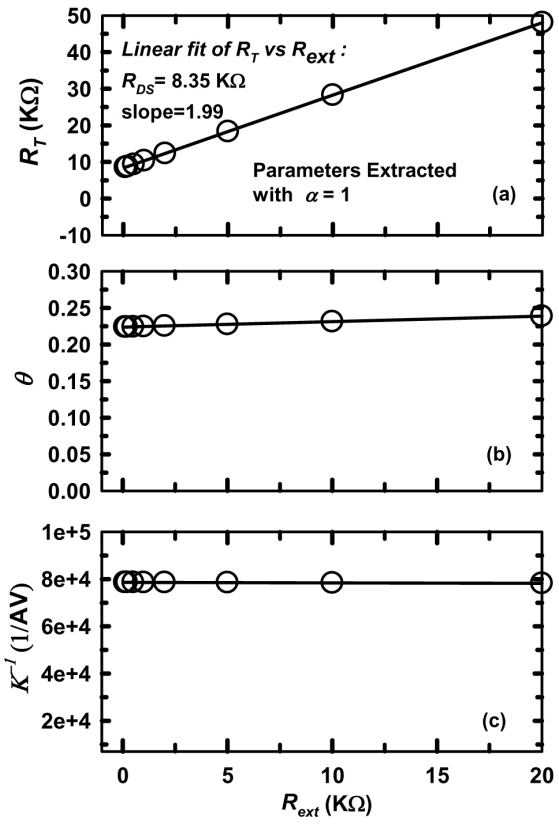

Figure 3. Extracted parameters vs external series resistance for α = 1.

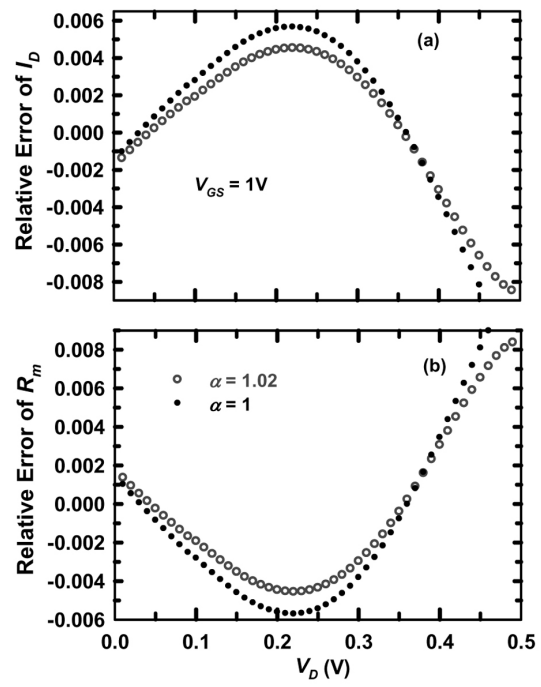

Figure 4. Relative errors of drain current (a) and source-to-drain resistance (b) using α = 1 (black dots) and 1.02 (blue circles), with V_{GS} = 1V.

its corresponding source-to-drain resistance, R_m, used in the extraction procedure. The resulting model playbacks calculated by using the extracted parameters are also shown in the same figure with solid lines. The maximum errors in drain current and total resistance are 0.24 μA and 5 Ω respectively.

Figure 6 shows the resulting model playbacks of the above-threshold transfer characteristics and the corresponding source-to-drain resistance, R_m, as functions of V_{GS} for the same 0.23 μm device at three low drain voltages (10, 20, and 50mV), together with the original measured experimental data. The extracted threshold voltage for this device is 0.65 V. The playbacks are shown only in the strong inversion region where the model is valid. Parameter θ only describes the mobility degradation for high gate voltages. It should be kept in mind that there is a region of moderate inversion for gate biases around the threshold voltage, for which neither the weak nor the strong inversion approximations are valid [15,16].

It is important to point out that the relative effect of R_{SD} diminishes as the channel length increases and that R_{SD} is nearly independent of the channel length. Therefore, we will assume that R_{SD} is constant for any channel length and that its value is equal to that extracted from the shortest channel length (0.23μm) device where its effect is most significant.

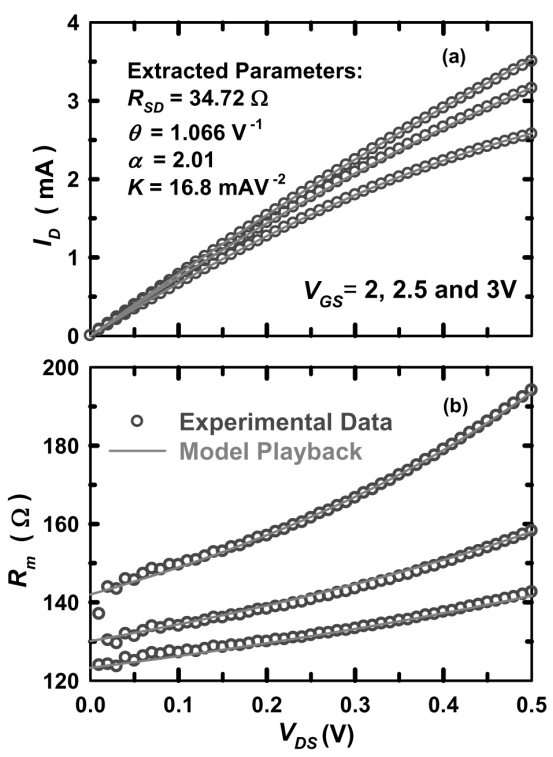

Figure 5. Experimental below-saturation output characteristics (a), and corresponding measured source-to-drain resistance (b), of a test 0.23μm channel device, measured at three above-threshold gate voltages (open circles). Also shown are the model playbacks (solid lines) obtained by using the extracted parameters.

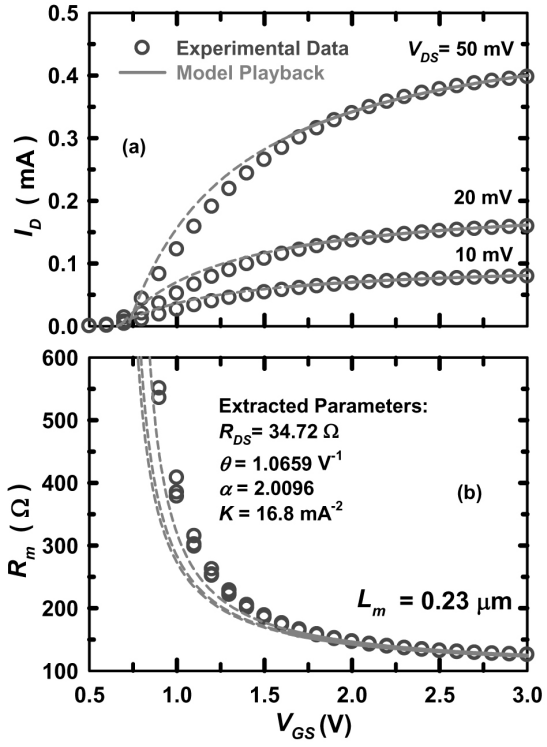

Figure 6. Experimental above-threshold transfer characteristics (a), and corresponding measured source-to-drain resistance (b), of a test 0.23μm channel device, measured at three low drain voltages (open circles). Also shown are the model playbacks (solid lines) obtained by using the extracted parameters.

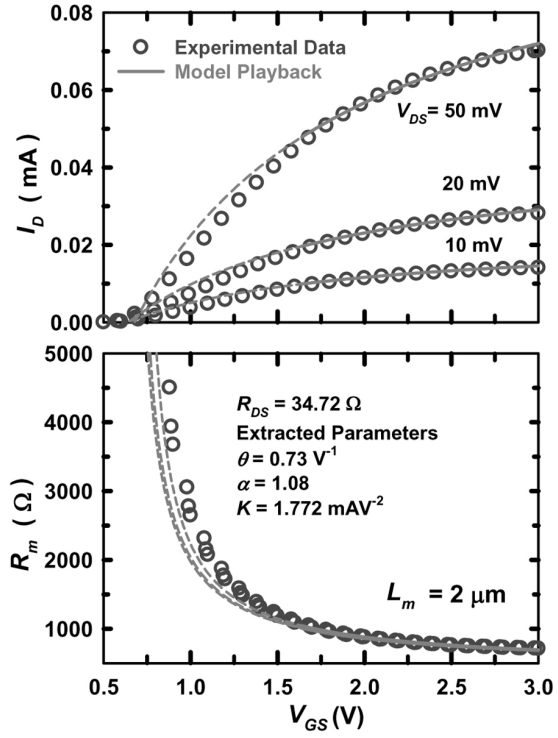

Figure 8. Experimental above-threshold transfer characteristics (a), and corresponding measured source-to-drain resistance (b), of a test 2μm channel device, measured at three low drain voltages (open circles). Also shown are the model playbacks (solid lines) obtained by using the extracted parameters.

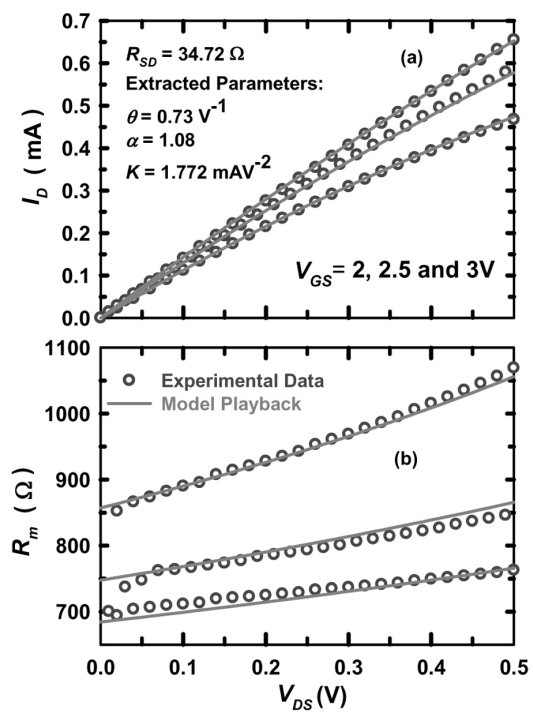

Figure 7. Experimental below-saturation output characteristics (a), and corresponding measured source-to-drain resistance (b), of a test 2μm channel device, measured at three above-threshold gate voltages (open circles). Also shown are the model playbacks (solid lines) obtained by using the extracted parameters.

Figures 7 and 8 present similar results for the longest channel device (2μm). The extracted threshold voltage for this device is 0.62 V. The resulting maximum errors in drain current and total resistance, presented in Fig. 7, are 12 μA and 20 Ω respectively. The parameters of two additional devices with intermediate channel lengths of 0.60 and 1μm were also extracted.

Regarding the computational efficiency of the indirect fitting procedure, for these experimental devices, the required number of iterations is less than 30 when using initial guess values for the parameters of about four times their actual values. Given that the same trend was observed for the previously shown simulated data, it seems reasonable to expect the same computational efficiency in general.

Figure 9 shows the evolution of the θ, α and K parameters as the mask channel length increases from L_m=0.23μm to 2.00 μm. A $\Delta_L = L_m - L_{eff}$ = 34nm may be estimated from the plot of K^{-1} versus L_m [17], which is consistent with the technology of these experimental devices.

Indirect bidimensional fitting procedures such as the one presented here could be applied to more complex models than the one represented by equation 1, allowing carrier velocity saturation and other short channel effects to be included[18].

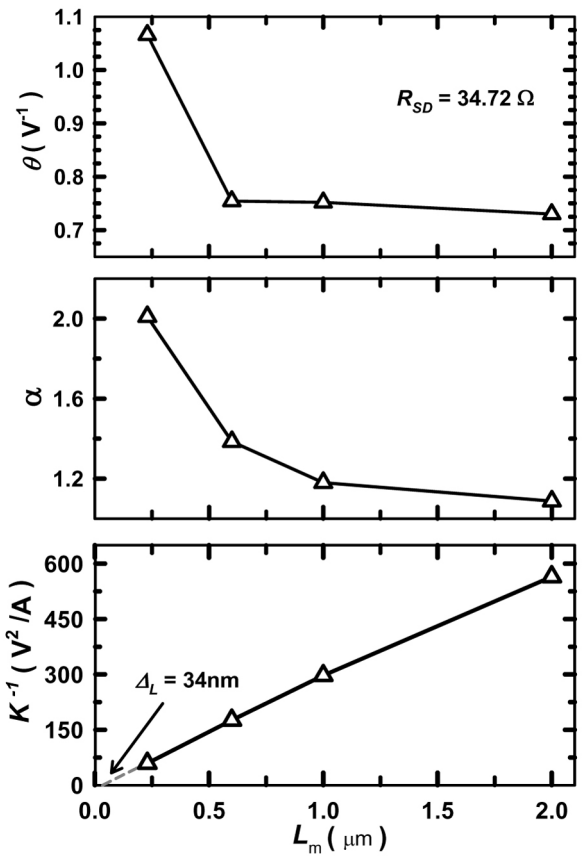

Figure 9. Evolution of the θ, α and K parameters with drawn channel length.

5. CONCLUSIONS

We have presented a procedure to separate and extract the mobility degradation factor and the source-and-drain series resistance parameters of MOSFET models, while also extracting the "α and K". The frequent difficulty encountered in separating the effects of source-and-drain series resistance and mobility degradation factor is overcome by using bidimensional fitting of the current-voltage characteristics model equations to the measured $I_D(V_{GS},V_{DS})$ data.

The most significant feature of this procedure is the use of indirect fitting of the source-to-drain resistance expression to the measured data of a single device. We have used the Sentaurus Device Simulator from Synopsys to simulate a triple gate FinFET with externally added resistances ranging from 100Ω to 20KΩ. Our results show that the value of R_{SD} can be extracted even in the presence of high external resistances. The procedure was then applied to a batch of DRAM MOSFETs, with channel lengths ranging from 0.23μm to 2.00μm and their model parameters were extracted as functions of the channel length. To get the best possible accuracy in a given batch of devices with various channel lengths, the series resistance should be extracted from the shortest channel device, if available, since its relative effect within the measured resistance is highest.

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